Transition to sustainability? Feasible scenarios towards a low-carbon economy

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Abstract

This paper analyses different policies that may promote the transition towards a low-carbon economy. We present a dynamic simulation model where three different strategies are identified: improvements in energy efficiency, the development of the renewable energy sector, and carbon capture and storage. Our aim is to evaluate the dynamics that the implementation of these strategies may produce in the economy, looking at different performance indicators, such as the GDP growth rate, unemployment, labour share, carbon emissions, and renewable energy production. Scenario analysis shows that a number of tradeoffs between social, economic and environmental indicators emerge. Such tradeoffs undermine an 'objective' definition of sustainability.

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1 Introduction

This work stems from the widespread perception that macroeconomic models do not help policy makers to deal with urgent problems. There are several reasons for this growing distance between economic theory and policy. It is undoubtedly related to the current social, economic and environmental crisis, and, at the same time, to the increasing difficulties that synthetic economic indicators have in describing the state of health of a country. In this paper, we take up this challenge by applying a macroeconomic model to a pressing problem, namely the reduction of carbon emissions. In building this model, we have often encountered the lack of explanatory power of orthodox theory when seeking to account for the many complex relationships between social, economic and environmental factors. The use of system dynamics, thanks to its graphical representation and its flexibility through simulations and scenario analysis, made the model richer and more comprehensive. Using this methodology, we move away from the dictates of economics. The goal is not to have a predictive model of economic policies required for sustainability, but to understand the dynamics that are set in motion, their magnitude, their interconnections and their feedbacks. While this may be a limitation, a sort of methodological encroachment, we believe we have at least partially moved "towards a human economics" (Boulding et al., 1974),[1] and a post-normal science (Funtowicz and Ravetz, 1990, 1991).

Our analysis shows that the changes required to achieve a significant reduction in carbon emissions will shake the socio-economic system, calling for a new balance of power within society. In particular, in our model, the implementation of strategies towards a low-carbon economy (hereafter LCE) affects the growth rate, unemployment rate and the distribution of income. The strength of such changes is perhaps the main explanation of the obstacles that nations face in signing agreements on emissions reduction. In the light of our analysis, the concept of sustainability cannot be defined as a state to be reached by the system. Given the emergence of strong tradeoffs in the transition to an LCE, sustainability takes on a political meaning: it is society itself which must define sustainability through the democratic process of choice (Costanza et al., 2014). This conclusion strengthens our conviction that feasibility analysis is the most advanced step that economic analysis can achieve today. Dwelling on the optimality of these paths towards an LCE would instead require an objective definition of sustainability and a social welfare function to maximise, which would soon result in methodological reductionism. If sustainability is a political concept, then it may change over time

[1]Towards a human economics was a statement produced in October 1973 by Nicholas Georgescu-Roegen, Kenneth Boulding and Herman Daly, and signed by more than 200 economists; it was first published in Italian and presented in December 1973 at the Annual Meeting of the American Economic Association.

according to changes in the system.

In our framework we aim to take into account this complexity in three stages. First, we build a simple macroeconomic model where the determination of wages and employment is a result of a modified Lotka-Volterra model. An increase in the employment rate – the prey – brings about an increase in the growth rate of wages – the predator. However, an increase in wages has a negative feedback on the growth rate of employment. This negative feedback creates a cyclical path in our scenarios which allows analysis of the dynamics of income distribution and unemployment.

Secondly, we integrate in the core of the model an analysis of the energy sector. While this sector is often underestimated in economic analysis, some recent European Commission publications recognize the development of an efficient energy system as a priority goal for Europe. Indeed, the European Commission seeks an 80% reduction in carbon emissions by 2050 with respect to the 1990 level (European Commission, 2011). We examine three strategies to achieve this goal: carbon capture and storage, investment in energy efficiency and the development of renewable energy sources. Such strategies can be seen as complementary in the transition to sustainability. Indeed, they all aim to control climate change and to reduce the dependency of the economy upon fossil energy sources. However, given budget constraints and irreversibility in investment decisions, the competition among them is quite strong. Scenario analysis is a powerful tool to evaluate the dynamics generated by alternative policies which tend to favour one of those strategies. Furthermore, we evaluate whether some policies rather than others can deal with the strong uncertainty concerning our future and prove more resilient and adaptive to changes. Finally, while the model can be easily adapted to different countries, we apply it to Italy, performing calibration and robustness analysis of the crucial parameters.

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The paper is organised as follows. Section 2 discusses the relevant literature. Section 3 presents the essential theoretical structure of the model and clarifies the main feedbacks characterising our model. Section 4 discusses the main results of the simulation through scenario analysis, and is followed by conclusions in Section 5.

2 Related Literature

Models that integrate energy, economy and society are generally defined as *integrated assessment models*. They are inherently interdisciplinary. The basic idea of this kind of tool is to identify sustainable scenarios from an energy and environmental point of view and to develop policy instruments that may promote the transition to an LCE. These models may be grouped into two broad classes, optimisation and simulation or non-optimisation models (Scrieciu et al., 2013).

Optimisation of some social welfare functions is the common basis of orthodox economic theory. Several models have been developed, amongst which the most widely used are the computable general equilibrium model (GEM-E3 (Capros et al., 1997)), optimal growth model (DICE and RICE model - (Nordhaus, 2008, 1993)) and neo-Keynesian models (DSGE). Despite the conceptual and methodological differences that can be detected between these different classes of models, there is a group of shared features related to the underlying assumptions, namely perfectly competitive markets, perfect information and the flexibility of factor prices. However, these assumptions do not allow for an investigation of income distribution and unemployment. We believe that such issues are crucial if the goal of the analysis is to provide support to policy makers.

Simulation models describe a number of interconnected relationships between economic and environment variables that allow us both to explore the propagation of disturbances into the system and to evaluate the effect of certain policy instruments in the economy, without the maximisation of a particular objective function. A wide range of models share this approach, among which we can mention models based on the post-Keynesian framework (Rezai et al., 2012; Foley et al., 2013), macroeconometric models (Cambridge E3MG model – Barker et al., 2012), evolutionary models (Sararzynska and van den Bergh, 2013) and others that make explicit use of system dynamics.[2]

The latter methodology is undoubtedly one of the most crucial features of our model. System dynamics is a suitable tool for the analysis of complex systems and is characterised by a high degree of flexibility and a graphical structure which allows identification of feedback mechanisms (Costanza and Ruth, 1998; Costanza et al., 1993). Developed by Jay Forrester at MIT in the 1950s, this tool has spread enormously in engineering research and can be used to represent both socio-economic and environmental systems.[3] In addition, scenario analysis provides the opportunity to deal with many sources of uncertainty.

System dynamics is, for economics, an unconventional modelling methodology

[2]For a recent and detailed survey on the features and assumptions of optimisation and non-optimisation models see Scrieciu et al. (2013).

[3]The methodology is based on three basic units. Stocks are any variable that accumulates or depletes over time. Flows indicate how the system is changing over time. Connectors are either simple numbers (parameters) or variables whose value is instantaneously determined by some equation, without any inflow or outflow. It allows for a modular approach to modelling, whereby different (and increasingly complex) elements can be bolted onto the core model, allowing a more or less detailed picture to be presented. For a simple and interesting introduction to the system dynamics approach for economic and environmental issues see for instance Bardi (2011).

that entails explaining the relationships between the various elements of a system. There are few attempts to develop macroeconomic models through system dynamics. A very interesting work is that developed by Yamaguchi (2011) which provides a model of an aggregate economy with a detailed representation of the main economic actors (consumers, producers, government, banks, the central bank).[4] There are also integrated assessment models in system dynamics which can be divided into two broad classes. The first class assumes an exogenous macroeconomic framework and focuses on issues such as environmental sustainability, energy transition and peak oil (Nail and Budzik, 1976; ASPO, 2008; Sterman, 1982; EIA, 2007). While these models explore the energy and the environmental side of the system, the absence of interactions between environmental policies and macroeconomic dynamics makes them difficult to use as policy instruments. To overcome this shortcoming, a second class of model investigates, in an integrated approach, energy, economy and the environmental system. A well-known model is *World 3*, the dynamic simulation model used in the "Limits to Growth" (Meadows et al., 1972). That model was further improved through the *World3/91* model used in "Beyond the Limits" (Meadows et al., 1991) and the *World3/2000* model distributed by the *Institute for Policy and Social Science Research*. Another work that deserves mention is the T21 project, developed by the Millennium Institute. It was recently used in the report "Towards a Green Economy" (UNEP, 2011).[5] This dynamic simulation tool is designed for long-run planning of national development, being able to support the comparative analysis of different policy instruments and to identify the set of policies aimed at achieving the desired objectives (Bassi, 2008; Bassi et al., 2010).

This work was inspired by Victor and Rosenbluth (2007), Victor (2008, 2012) who provide a macroeconomic model calibrated for Canada, where they analyse the possible impact that scenarios of low growth or negative growth can have on environmental and macroeconomic variables such as income, poverty, unemployment, public expenditure and greenhouse gas emissions. Unlike them, we explicitly model the strategies towards LCE and their interconnections with the macroeconomic system. Our fundamental goal is not to ascertain whether it is possible to disentangle wellbeing and economic growth, but to evaluate the changes required to reduce carbon emissions and analyse the effects of those changes upon the socioeconomic system. Furthermore, we show that the transition to LCE reduces the dependence of wellbeing upon economic growth since strong tradeoffs between the rate of growth and other social and environmental indicators emerge.

In conclusion, this contribution is part of the so-called *Ecological Macroeco-*

[4]Another example is the Macrolab model, developed by Wheat (2003), focusing on the US economy.

[5]Different applications of this model can be seen at `www.millenniuminstitute.org/integrated_planning/tools/T21/`.

nomics (Victor and Rosenbluth, 2007; Jackson, 2009; D'Alessandro et al., 2010; Jackson and Victor, 2011; Rezai et al., 2012) which aims to solve macroeconomic dilemmas such as "the balancing of consumption and investment while maintaining high employment as well limits on material consumption" (Harris, 2009, p. 42) in a strong sustainability perspective, where the complementary relationship between natural capital and physical capital, and between flows and stocks of resources are preserved (Daly, 1996).

3 Modelling the Transition to LCE

3.1 The analytical framework

Figure 1 shows an overview of the structure of our economy. We use it to discuss the most interesting features of the model and some crucial assumptions. A complete list of variables (and parameter values) and equations can be found in the Appendices A and B respectively.

Before entering into the details of the analytical model, it is worth clarifying the structure of the system. Following Figure 1, three subsystems can be distinguished. The first is the ordinary positive feedback of economic growth, which links production to investment through disposable income, and investment to production through the change in the stock of physical capital. The second subsystem concerns determination of employment in the final sector. It is affected by technology, wages and labour productivity; on the other hand, employment contributes to determine output and wages. The third subsystem takes into account energy as an essential input. Energy demand is determined by the degree of energy efficiency. Investments can be diverted to increase energy efficiency, to develop a renewable energy sector, and for carbon capture and storage. These are the three strategies that may be able to move the system towards an LCE. Below, we take into account several interactions between those subsystems and discuss some crucial feedbacks after the presentation of the analytical model.

Production. The economy produces a composite homogeneous good by a CES technology with energy as a complementary input. Following a long tradition in ecological economics (Georgescu-Roegen, 1971), we assume complementarity both for theoretical and empirical reasons.[6] Final good production takes place according to the following technology

$$Y_t = \min\left\{f\left(L^F, K, \lambda, t\right), \epsilon_t E_t\right\}, \tag{1}$$

[6]For a brief summary of the theoretical and empirical reasons on complementarity between energy flows and physical capital, see for instance D'Alessandro et al. (2010, p. 292).

with

$$f(L^F, K, \lambda, t) = \Lambda \left[\alpha \left(\lambda_t L_t^F \right)^{\frac{\theta-1}{\theta}} + (1-\alpha) \left(\kappa_t K_t \right)^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}}, \tag{2}$$

where the index t represents time, $\Lambda > 0$ and $0 < \alpha < 1$ are technological parameters, θ is the elasticity of substitution, K is the capital stock, L^F is the employment in the final sector, E is the flow of energy and ϵ is the inverse of energy intensity which measures the energy efficiency. We assume a CES technology since it allows for a differentiated technological change in capital and labour. Indeed, while the rate of change in the productivity of capital κ is exogenous and equal to g_κ, the labour productivity changes according to the capital stock, that is

$$\lambda_t = \zeta K_t^{\mu}, \tag{3}$$

where $\zeta > 0$ and $0 < \mu \leq 1$. This feature means that the accumulation of capital produces a positive externality on labour productivity. We discuss the relevance of such an assumption in the following section.

Energy sector. As we pointed out above, in order to meet the target in the reduction of carbon emissions, three strategies are considered in the model. We discuss them in the paragraph "Investment strategies". Since they are strictly linked to energy use, we refer to the "energy sector" to identify the set of economic variables that are directly affected by those policies. The energy sector comprises the following services supplied to the overall system: i) fossil energy transformation, ii) efficiency improvements, iii) direct reduction in carbon emissions, iv) renewable energy production. The labour required for each of those services determines the employment in the energy sector, L^E. Following Wei et al. (2010), we assume that i) employment in fossil energy transformation L^Q is a linear function of Q, ii) employment in efficiency improvements L^ϵ is proportional to the energy saved every period, iii) employment in direct reduction in carbon capture and storage L^M is proportional to the CO_2 saved every period, iv) employment in renewable energy is split into direct and indirect labour, direct workers L^H are proportional to the flow of renewable energy H, and indirect workers L^R are given by the change in the renewable energy capacity ΔR.[7] Thus, total employment in the energy sector is

$$L_t^E = L_t^H + L_t^R + L_t^\epsilon + L_t^M + L_t^Q. \tag{4}$$

Total employment in the economy is $L = L^I + L^E$. Thus, employment rates are defined as the ratio between the number of workers employed in the final and in the energy sector over the total labour force, i.e. v^I and v^E respectively.

[7] The explicit form of the equations can be found in the Appendix B, equations $B.30 - B.38$.

Employment and wage. Employment in the final sector and wages are determined by the following system of difference equations:

$$\begin{cases} g_{v^I} = (A_t^{LV} - B_t^{LV} w_t) & (5) \\ g_w = (C_t^{LV} v_t^I - D_t^{LV}). & (6) \end{cases}$$

where, v^I is the employment rate in the final sector, w is the wage, $g_{v^I} \equiv \frac{v_{t+1}^I - v_t^I}{v_t^I}$, $g_w \equiv \frac{w_{t+1} - w_t}{w_t}$. This system is a Lotka-Volterra model (Volterra, 1926; Lotka, 1932), in which an increase in the employment rate v^I – the prey – brings about an increase in the rate of growth of the wage w – the predator. However, an increase in w has a negative feedback in the rate of growth of v^I. If the variables A^{LV}, B^{LV}, C^{LV} and D^{LV} are constant the dynamics of the system would follow a limit cycle around the unique internal equilibrium. This framework for the determination of employment and wages was developed by Goodwin (1967) in a simplified growth model. Three assumptions in our model significantly alter the classical Goodwin model: i) the output-capital ratio changes over time, see equations (1) and (2); ii) labour productivity changes according to equation (3); iii) increasing efficiency and the development of a domestic energy sector need labour and affect the labour market. Such features mean that A^{LV}, B^{LV}, C^{LV} and D^{LV} explicitly depend on GDP, capital, labour productivity, employment in the final sector and in the energy sector. We assume the following relations:

$$A_t^{LV} = \sigma_1 \frac{GDP_t}{K_t} - n - \lambda_t, \quad (7)$$

$$B_t^{LV} = \sigma_2 \frac{L_t^I}{K_t}, \quad (8)$$

$$C_t^{LV} = \sigma_3 \lambda_t^{\nu}, \quad (9)$$

$$D_t^{LV} = \sigma_4 - \sigma_5 v_t^E. \quad (10)$$

where $n \geq 0$ is the exogenous population growth rate, v^E is the employment rate in the energy sector, $\sigma_i > 0$ for any $i = 1, \ldots, 5$ and $0 < \nu < 1$. Equations (5) and (7) mean that an increase in the output-capital ratio produces an increase in the rate of employment in the final sector, while population growth rate and labour productivity have the opposite effect. Equations (5) and (8) mean that an increase in wages produces a reduction in the employment rate proportional to the labour-capital ratio.[8] Equation (9) means that the increase in labour productivity generates a surplus that is partly captured by workers through an increase in the

[8]In a different way, if the technology is more labour intensive, the increase in wage has a stronger negative impact on the employment rate.

wage rate.[9] Finally, equation (10) means that the employment rate in the energy sector directly affects the wage rate. Since energy production is an intermediate sector and labour productivity is only linked to the final sector, in the model the two employment rates are distinguished, and through the parameter σ_5 it is possible to differentiate their impacts on wages. Our hypothesis in the reference scenario is that changes in the employment rate in the energy sector affect the wage rate of the economy less than changes in the employment rate in the final sector.[10]

Figures 2a and 2b show the change in the Lotka-Volterra model whether the variables A^{LV}, B^{LV}, C^{LV} and D^{LV} are constant or change over time according to our conjectures. More precisely, in both the Figures – 2a and 2b – the initial values of A^{LV}, B^{LV}, C^{LV} and D^{LV} are the same, but while in 2a they are kept constant, in 2b they change according to the reference scenario of the simulation. As is evident in Figure 2b, the fixed point of the dynamic system changes in time and the "playing forces" tend to stabilise the system.[11] Figures 2c and 2d show that the employment rate in the final sector and the wage move around the equilibrium. Since there is a growth trend in the model, the fluctuations of the employment rate tend to be above the equilibrium level. The opposite occurs for the dynamics of wages.

Fossil energy and GDP. We consider two composite energy sources, fossil fuels and renewable energy, and we use the standard, albeit strong, assumption that the two types of energy are perfect substitutes

$$E_t = Q_t + H_t, \tag{11}$$

where Q and H are the flow of fossil fuel and renewable energy resource, respectively. The flow of energy is linear in the renewable capacity R, that is

$$H_t = hR_t, \tag{12}$$

with $h > 0$.

Given the absence of substitutability of energy flows in the production process, technical efficiency requires the following quantity of fossil energy

$$Q_t = \frac{f\left(L^F, K, \lambda, t\right)}{\epsilon_t} - H_t. \tag{13}$$

[9] The parameter ν measures the elasticity of C respect to λ, that is the sensitivity of wage to the increase in labour productivity.

[10] This assumption does not affect the main results of the model. However, we discuss it in detail through sensitivity analysis in section 4.2.2.

[11] This result is consistent with some extensions of the Goodwin model. See for instance Flaschel (2010, ch. 4.3) and references therein.

Since fossil energy sources are imported from abroad, its relative price plays an important role in the determination of the net product. For simplicity, we further assume that the country is a small open economy. Thus the international price of fossil fuel p is not influenced by domestic demand. The price of Q changes in time at a constant rate π. Hence the GDP of the economy is given by the production less the cost of fossil energy,

$$GDP_t = Y_t - p_t Q_t. \tag{14}$$

Disposable income. Mobility of workers between the two sectors implies that wages are the same. Thus gross total wage is given by

$$W_t = w_t L_t^I + w_t L_t^E, \tag{15}$$

and as a consequence, profits are given by

$$\Pi_t = GDP_t - W_t. \tag{16}$$

We consider that the above two sources of income can be taxed differently by the government, that is

$$T_t = \tau_1 \Pi_t + \tau_2 W_t. \tag{17}$$

Moreover, the government can provide unemployment benefits. We assume that such benefits increase when unemployment u_t exceeds a certain threshold $\bar{u}$,

$$TR_t = \beta_1 GDP_t + \beta_2 (u_t - \bar{u}). \tag{18}$$

We assume that, in any period, government budget is balanced, i.e. tax revenue equals public expenditure plus unemployment benefits.[12] Thus $G_t = T_t - TR_t$. Disposable income (Y^D) is given by

$$Y_t^D = (1 - \tau_1)\Pi_t + (1 - \tau_2) W_t + TR_t. \tag{19}$$

One of the basic assumptions of the original Goodwin model is that wages are entirely consumed and profits are fully reinvested. In this model, in order to stress the importance of the functional distribution of income, we assume that the marginal propensity to consume across sources of income is different. Of course, the propensity to consume from profits (γ_1) is no lower than that from labour (γ_2), that is $\gamma_1 \geq \gamma_2$. This assumption is crucial because we want to preserve the

[12] The model can easily be generalised to take into account that part of the public budget must be diverted to cover interests on debt and to reduce public debt. However, such an analysis goes beyond the scope of this paper.

characteristic that profits lead the growth process of our economy. Hence, savings in the economy are given by

$$S_t = (1-\gamma_1)(1-\tau_1)\Pi_t + (1-\gamma_2)[(1-\tau_2)W_t + TR_t]. \tag{20}$$

Investment strategies. Two different approaches can be used to establish investments. The first defines investments through a behavioural equation which depends on income and tends to increase if aggregate demand in the economy exceeds aggregate supply – that is if investments are higher than savings. This disequilibrium approach generates short-run cycles.[13] However, since the determination of employment and wage through the Lotka-Volterra model generates by itself a cyclical effect, we prefer to avoid an additional adjustment mechanism which would make the simulations less comprehensive. For this reason we simply assume that the amount of investment in the economy is always equal to savings. Thus, from equation (20)

$$I_t = (1-\gamma_1)(1-\tau_1)\Pi_t + (1-\gamma_2)[(1-\tau_2)W_t + TR_t]. \tag{21}$$

This amount of resources is diverted to the accumulation of four stocks: i) physical capital, ii) renewable energy capacity, iii) carbon capture and storage, iv) reduction in energy intensity. In particular,

$$I_t = I_t^K + I_t^R + I_t^M + I_t^\epsilon. \tag{22}$$

Capital varies according to the usual accumulation law

$$K_{t+1} = (1-\delta^k)K_t + I_t^K. \tag{23}$$

Following D'Alessandro et al. (2010), R changes according to the following accumulation function

$$R_{t+1} = I_t^R\, f(R_t) + R_t - \delta^R(R_t - \bar{R}), \tag{24}$$

where δ^R is the depreciation of installed capacity per unit of time, and $\bar{R}$ is a minimum level of renewable energy capacity which represents the ability of humans to exploit alternative energy sources (such as biomass) without investing in such sources, and the marginal productivity of investments in renewable energy capacity depends on the stock of renewable energy through $f(R_t)$ that we assume to be a logistic function.[14]

[13]In Bernardo and D'Alessandro (2014), we explored the effect of this assumption on a similar model.

[14]Equation $B.4$ in the Appendix B explicitly shows the logistic function used. This function takes into account the diffusion of knowledge arising from the increase in the level of R.

Similarly, energy efficiency, ϵ_t changes according to the following function

$$\epsilon_{t+1} = \epsilon_t + I_t^{\epsilon}\, g(\epsilon_t), \tag{25}$$

where $g(\epsilon_t)$ measures the marginal productivity of investment in efficiency improvements.

For the sake of simplicity, we assume that only fossil energy produces carbon emission according to a linear function $P_t = \phi_t Q_t$. The variable ϕ_t indicates the amount of carbon emissions produced with one unit of fossil energy. Investments are necessary in order to reduce ϕ_t, that is,

$$\phi_{t+1} = \phi_t - I_t^{\phi}\, h(\phi_t), \tag{26}$$

where $h(\phi_t)$ determines the marginal productivity of investment in GHG reduction.

Calibration The model was calibrated by using annual frequency data. The reference year is 2010 and different sources of data were employed, namely: ISTAT dataset[15] for macroeconomics and accounting variables, ENEA (2012) dataset for energy consumption and production, Terna dataset[16] for renewable energy sources; Observ'ER report (Liebard, 2012) for a measure of employment in the energy sector, and Wei et al. (2010) to estimate the numbers of workers per Mtep of energy produced with renewable and fossil sources or saved through specific investments in energy efficiency. To ensure the transparency and the replicability of the model, a complete list of parameters and initial values can be found in Appendix A. Moreover, we discuss in Sections 4.2 and 4.3 some specific assumptions and numerical experiments.

3.2 System mapping and feedback loops

The description of the model can be clarified through a brief discussion of the interactions among its subsystems. Figure 3 shows the feedback emerging from the model. The colours of the variables are consistent with the structural representation given in Figure 1. Yet in Figure 3, we highlight the main causal relations among the elements of the overall system.

The first important feedback (the blue boxes and arrows) emerges in the associated determination of wages and employment through the Lotka-Volterra model. This is clearly a stabilising feedback: the increase in employment brings about an increase in wage that in turn tends to depress employment – see equations (5) and (6).

[15] http://dati.istat.it/?lang=en

[16] http://www.terna.it/default/Home/SISTEMA_ELETTRICO/statistiche/dati_statistici.aspx

Employment and wages contribute to the determination of production and labour share respectively. Those two relations clarify the interaction between this subsystem and the evolution of the global system. Let us assume that no strategy for LCE is implemented – hence investments are totally used in the accumulation of physical capital – and that productivity is constant. Under these assumptions, an increase in investments brings about a further accumulation in the stock of capital – equation (23). This in turn produces an increase in output and GDP, despite the reduction due to the increase in the use of fossil energy – equation (14). The increase in GDP tends to increase investments in a reinforcing feedback. However, it also affects the determination of employment and wages, namely the first subsystem. In particular, GDP has a positive effect on employment – equations (5) and (7) – and this in turn increases wages. The simultaneous increase in employment and wages increases the labour share and, since labour income has a lower propensity to save than profits – see equation (20) – it shrinks the increase in investments. This is the main interaction between the two subsystems.

This picture is made more complex given the changes in labour productivity associated to the increase in the stock of capital – equation (3). Labour productivity generates a positive feedback to production, since it reinforces the growth cycle – more capital $\rightarrow$ more labour productivity $\rightarrow$ more production $\rightarrow$ more investment, and so on – but it also tends to reduce employment and to augment the wage level – equations (7) and (9). The net impact on the labour share and hence on investments depends on the relative size of the two effects. Indeed, an increase in the scale of production through capital accumulation increases employment through the increase in GDP, but it reduces the labour-capital ratio and this dynamic tends to reduce employment – equation (8). Since GDP depends on the cost of fossil fuels, if energy efficiency is low, an increase in the stock of capital and production may result in a reduction of employment.

The final step is the inclusion of the strategies towards LCE. For the sake of clarity, in the model we assume that the only channel for implementing such strategies is to divert investments from the accumulation of physical capital to "green strategies", that is i) the improvement of energy efficiency, ii) the development of domestic renewable energy production, iii) the progress in carbon capture and storage technologies.[17] The first important consequence is that there is a fall in investment in physical capital, which in turn leads to a sequence of effects according to the causal loop investigated above. A second major consequence is that the first two strategies result in a reduction in the demand of fossil energy – equation (13) – thus GDP tends to increase. The last consequence directly affects the

[17]Obviously, different channels can be considered, such as direct public investment founded by taxes in consumption, in labour income or profits. However, we believe that in analysing a growth model, investment is the crucial variable and we therefore limit our analysis to this issue.

job market. Since the development of the "green sector" requires workers, green strategies shape the determination of wages and employment. In particular, the economy initially faces an increase in employment and wages, but this latter effect produces a reduction in labour demand in the final sector – equation (10). The final result is not obvious and we discuss it extensively in the scenario analysis.

4 Dynamic Simulation and Scenario Analysis

4.1 Baseline scenarios

Our scenarios are based on the Annual Report on Energy and Sustainable Development published by ENEA that investigates the Italian energy sector and its possible development. This analysis is processed through the TIMES-Italy, namely a model generator for the national energy systems which estimates energy dynamics over a long term time horizon (Loulou and Labriet, 2008).

The energy side of the ENEA model is very detailed, comprising many many systems of equations and inequalities which represent the set of energy sources used in the economy. Moreover, for each type of resource, the whole energy cycle (production, distribution and consumption) is considered by including technological parameters (i.e. efficiency, power, life cycle), economic variables and emissions derived from these activities. Finally, the model is fully calibrated using Eurostat Energy Statistics.

The energy model is integrated with an exogenous macroeconomic framework. In particular, the main macroeconomic variables – i.e. GDP growth rate, price of fossil energy sources – are calibrated using current trends and long term projections on population and the economy provided by Eurostat and EPC/ECFIN. On the other hand, there is no feedback between strategies towards LCE and the macroeconomic setup.

Figure 4 shows the three scenarios that are provided by ENEA (2012) for the period 1990-2030. The first is called the "Reference Scenario" (blue) and determines the evolution of the system in the absence of policy intervention. In this scenario, both the amount of primary energy consumption and carbon emissions will increase slightly from current values to 2030. The second is the "Current Scenario" (red) which represents the effects of steady implementation of current energy policies, that are based on the National Plan for Energy Efficiency (PAEE 2010) and the National Plan for Renewable Energy Sources (PANER 2010). The result is a 10% reduction in primary energy consumption and 14% in CO_2 emissions in 2030 with respect to the Reference Scenario. The third is the "Roadmap Scenario" (green) which shows the simulation results of the additional policy interventions and the necessary changes for the Italian energy system to meet Impact

	ι_ϵ	$\iota_{\mathbf{R}}$	$\iota_{\mathbf{M}}$	**Green Investment (%)**	**Green Investment Ratio (%)**
Reference	0.01	0.01	0.001	2.1	0.5
Current	0.025	0.06	0.001	8.6	1.8
Road Map	0.08	0.19	0.011	28	5.6

Table 1: Investment Strategy. Variables ι_ϵ, ι_R, ι_M are the share of investment in energy efficiency, in renewable energy development and in carbon capture and storage, respectively. 'Green Investment' (%) is total share of investment diverted to the three strategies; the 'Green Investment Ratio' is the ratio between the amount of green investment and the GDP at the end of the period.

Assessment criteria for 2050 European Commission (2011). In this case, in 2030, there is a respective 17% and 40% reduction, respectively, in energy consumption and CO_2 emissions compared to the Reference Scenario.

As an investigation strategy, we replicated the ENEA scenarios in terms of primary energy consumption and carbon emissions, by choosing a certain amount of investment in the three strategies discussed above. Table 1 shows the values of the share of total investments diverted into the three strategies, where ι_ϵ, ι_R, ι_M are the share of investment in energy efficiency, renewable energy development and carbon capture and storage, respectively..[18] The columns "Green Investment" and "Green Investment Ratio" capture the size of the effort towards LCE as the percentage of the total investment and as the share of GDP respectively. Figures 5 and 6 present the results in terms of GDP, unemployment, labour share, rate of growth, renewable energy share, green jobs, energy use, and carbon emissions. The scenarios take the price of fossil fuels as given; the simulation period starts in 2010 (period zero in the figures) and is run for 40 years.

In the reference scenario, the very low level of green investment does not produce any reduction in carbon emissions, even if energy intensity slightly decreases. More precisely, the system would face an almost constant share in renewable energy production (Fig. 6c) and a minimal increase of workers in the energy sector (Fig. 6d) driven by an increase in employment in fossil energy transformation. On the socio-economic side, we have a number of interesting results. First, the GDP increases on average by about 1% per year (Fig. 5b). Second, given our assumptions related to the determination of wages and employment, socio-economic indicators show a marked cyclical pathway. Furthermore, the number of workers in the final sector is slightly increasing, but this growth is not sufficient to compensate for the increase in the labour force (2% per year). As a consequence, the unemployment rate increases from about 8.4% in 2010 to 11% in 2050 (fig. 5c),

[18]More precisely, we assume that the policy gradually changes the share of investment in a few years. In Appendix A, we show the form used in the simulations.

and the labour share declines from 67% to 60% (fig. 5d). Growth is driven by the fact that in every period the stock of productive capital increases (fig. 5f), which positively affects labour productivity λ. This in turn brings about an increase in the wage level (fig. 5e) and a fall in the units of labour required in the production process.

In the current scenario, the level of green investment increases with respect to the reference scenario. The initial values of ι_ϵ, ι_R are the same as in the reference scenario up to 2014, and then they slowly increase up to 0.025 and 0.06 in six years.[19]

After this transition, 8.6% of the total investment is allocated to green energy policies. These resources, 1.8% in terms of GDP in 2050, are sufficient to replicate the Current Policies Scenario by ENEA (see table 1). As a result, GDP is slightly lower than in the reference scenario with an average growth rate of 0.87% (fig. 5b). Moreover, the unemployment rate is lower (fig. 5c) due to lower capital accumulation (fig. 5f) and hence lower labour productivity. Furthermore, investments in green strategies increase employment in the green sector up to 230,000 units in 2050 (fig. 6d). Finally, there is an improvement in terms of environmental indicators with a 17% reduction in carbon emissions (fig. 6b) and 15% in primary energy consumption (fig. 6c). Thus, in order to achieve a consistent reduction in carbon emissions, green investments must significantly increase w.r.t. the reference scenario. Nevertheless, the resources diverted to green policies in the current scenario are not sufficient to achieve the target.

According to ENEA, to achieve an 80% reduction in carbon emissions, the system should follow the roadmap scenario. In our model this path can emerge through a significant increase in investment in the three green strategies. Table 1 displays the values of ι_i for $i = \epsilon, R, M$ able to meet this goal. Green investment accounts for 28% of total investment, which is 5.6% of GDP at the end of the period.[20] The diversion of these resources from capital accumulation negatively affects the growth rate, which is equal, on average, to 0.6% per year (fig. 5b). The stock of capital stops growing after ten years and slightly diminishes later (fig. 5f). Reduction in the stock of physical capital does not stop GDP growth, since wages decrease enough to allow an increase in employment in the final sector. On the other hand, the lower labour productivity in the final sector and higher employment in the green sector allow a significant reduction in unemployment, from 8.4% in 2010 to 6.7% in 2050 (fig. 5c), four percentage points lower than in the reference scenario. Furthermore, this scenario brings about a slight increase in the labour share. Implementation of the roadmap scenario produces a reduction

[19]See Table 2 in Appendix A for additional details of the functional form adopted.

[20]In the simulation such values of policy measures are reached in twelve years after the first implementation of the policy. See Table 2 of Appendix A for simulation details.

of about 38% in primary energy consumption [21] (fig. 6c) and an increase in the share of renewable energy up to 60% of total energy production (fig. 6a).

As pointed out in the introduction, the aim of this contribution is not to provide a predictive model. However, our results suggest that, unlike the Stern Review on the Economics of Climate Change (Stern, 2007), an investment between 1% and 2% is not sufficient to achieve the 80% reduction in carbon emissions required to keep the increase in temperature below two degrees. Following the roadmap requires more than 5% of GDP. This significant amount of resources shakes the socio-economic system. Few important tradeoffs emerge from our analysis. First, the reduction in carbon emissions induces a reduction in the rate of growth. This slowdown does not result in social instability.[22] On the contrary, the rate of unemployment falls and the labour share increases by reducing inequality in society. However, in the roadmap scenario average wages grow at a lower rate than in the reference one, so even workers may be against these policies. This conclusion strengthens our conviction that the transition to an LCE is not easily implemented.

4.2 Sensitivity analysis

How does the model react to changes in the values of parameters? We are aware that a wide range of factors can affect the system given the complexity of the model and the long time horizon of our analysis. However, we focus on a few factors linked in some way to the energy side of the system.

4.2.1 Price of fossil energy sources

The first investigation concerns the price of fossil energy sources. In the baseline scenarios, we assumed that this price is constant over the simulation period. We present a comparison between the reference and roadmap scenario in three different cases (Figure 7): i) a fossil price reduction of 1% per year, ii) a fossil price increase of 1% per year, iii) a fossil price increase of 4% per year. While the first two cases illustrate two possible paths in the relative price of fossil fuels in terms of GDP, the third aims to capture the effects of an energy shortfall upon the economy.

In terms of GDP, the 1% decrease (increase) in the energy price positively (negatively) affects the growth rate and is particularly favourable (unfavourable) to the reference scenario with an increase (decrease) in the average rate of 0.05% (0.1%) w.r.t. the constant fossil price scenario (Fig. 7a). These differences in the growth rate lead to a 6% variation in GDP at the end of the period between

[21] 86 Mtep less than in the reference case

[22] This result is a common finding of a number of contributions on the relation between low growth and wellbeing; see for instance Victor and Rosenbluth (2007); Jackson (2009); Jackson and Victor (2011); Bilancini and D'Alessandro (2012); Victor (2012).

the two cases. This difference is less pronounced in the roadmap scenario. The main result in the first two cases is that this significant change in the fossil price does not produce any significant qualitative change in the system, which proves to be resilient to this change. However, Figure 7b shows that the gap between reference and roadmap scenario tends to decrease as the energy price increases in the first two cases. In the third case, a marked change between the two scenarios emerges. The drastic increase in fossil price triggers a recession in the reference scenario, while in the roadmap scenario, the system continues to follow a modest growth path. The intuition is straightforward: the high degree of investment in the development of a renewable energy sector reduces the dependence of production on fossil energy sources. Thus, the economy is less affected by changes in the fossil energy price. Finally, as expected, in the reference scenario, the fossil price increase tends to slightly reduce the carbon emissions (Fig. 7c) and the primary energy consumption (Fig. 7d). On the contrary, in the roadmap scenario, a fossil price increase results in a slight increase in carbon emissions. Indeed, the increase in the fossil price reduces the amount of resources which can be diverted to green investments, which slows down the transition to an LCE.

4.2.2 Green jobs

The second investigation concerns the net effect of environmental policies on green job creation. We analyse how the overall system reacts to change in the number of jobs attained through investments in the three strategies towards an LCE. As described in Section 3.1, we calibrate the number of workers per energy produced – employment in fossil energy transformation or renewable energy sector – or saved – employment in energy efficiency improvement – by using the same methodology as Wei et al. (2010). In the baseline scenario we assumed that the number of workers per unit of energy is constant. It is, however, plausible that the required units of labour change over time. We investigate two contrasting options: whether the number of workers per unit of energy increases or decreases at constant rate.[23]

Figure 8 shows the results of this change in the roadmap scenario. We refer to the scenario in which the number of workers created per unit of energy increases (decreases) over time as positive (negative), while in the neutral scenario the values are set according to the baseline simulation. In the positive scenario, green employment increases up to 1.2 million in 2050, three times more than in the negative scenario (Fig. 8d). This positive estimate is still consistent with several analyses of green job creation along the roadmap – see, for instance, ENEA (2012).

[23] More precisely, in Appendix B, the growth rates in equations B.38, B.36 and B.37 are equal to $g_{\varrho^i} = -0.015$ and $g_{\varrho^i} = +0.015$ for all $i = \epsilon, H, R$ in the positive and negative case, respectively. These changes can be interpreted as an increase or a decrease in labour productivity in the green sector which may require more or less labour as long as the scale of the sector increases.

According to our model, the increase in green jobs tends to slightly reduce GDP growth. The intuition is straightforward: the increase in employment produces an increase in wage that increases the labour share (Fig. 8c), which in turn reduces the investment and slows down the accumulation of capital (Fig. 8a).

Hence, an increase in job creation opportunities in the transition towards an LCE induces an increase in the level of wages. An important tradeoff between functional distribution – more favourable to labour – and GDP growth emerges. While this result is independent of the elasticity of wages to employment in the energy sector, such elasticity determines the result in terms of unemployment. In the baseline scenario, this elasticity is smaller than that of the workers employed in the final sector. Under this hypothesis, the rate of unemployment decreases when environmental policies create more jobs (Fig. 8d).

Figure 9 shows the effect on the unemployment rate of different hypotheses on the elasticity of wages with respect to the employment rate in the energy sector – σ_5 in equation (10). Equation 6 in the Lotka-Volterra system determines the level of wages and will affect the rate of employment in the final sector. By changing the numerical value of σ_5 it is clear that workers in the green sector have a different weight in determining the average wage. According to the previous analysis on job creation, we investigate the result in terms of the unemployment rate when four different values of σ_5 are considered. In order to facilitate comparison we report in Figure 9b the baseline scenario in which we assume that σ_5 is equal to 2/3. Figure 9a shows the case in which workers in the energy sector do not affect wage determination (σ_5=0). In this case the increase in green jobs has no negative effect on the employment rate in the final sector. Hence the total unemployment rate decreases more than in the baseline scenario. If we assume that $\sigma_5 = 2$, that is energy workers affect wages in a very similar way to workers in the final sector, then the increase in energy workers does not affect the total unemployment rate (Fig. 9c). The reason is that the increase in green jobs is totally offset by the reduction in employment in the final sector. Finally, when we assume σ_5=4, the increasing number of green jobs brings about growth in the level of wages that negatively affects the overall level of employment (Fig. 9d).

To summarise, a growth in green jobs brings about an increase in wages which shrinks the employment rate in the final sector, slows down GDP growth and increases the labour share. However, the effect on the overall level of unemployment depends on the elasticity of wages to the employment rate in the energy sector. If this elasticity is high (low) the effect of an increase in green job creation on the unemployment rate can be negative (positive). This elasticity can be interpreted as the bargaining power of green energy w.r.t. final sector workers. If they can obtain higher wages, then wage determination in the final sector may be strongly affected by the employment rate in the energy sector. While in this sensitivity exercise we only focused on the effect of green employment on wages, the system would also be affected by changes in wage elasticity to the employment rate in the final sector.[24]

4.3 Decoupling and dependence on fossil energy sources

In our model, the roadmap scenario is the path of the overall system that meets the carbon emissions target through a certain amount of green investments. While all three strategies highlighted in the paper contribute to this goal, we explore in this section whether one specified basket of strategies rather than others can achieve the policy objective when the attainable level of decoupling is uncertain.

The concept of decoupling is becoming increasingly used in mainstream environmental economics as the only instrument capable of attaining both a continuous growth in consumption levels and a substantial absolute reduction in environmental pressure.[25] The intensity in the use of raw materials, fossil energy and carbon emissions per unit of GDP has declined over the past three decades in particular in OECD countries.[26]. As Figure 10 shows for Italy, energy use and carbon emissions has grown at a lower rate than GDP. Thus there has been relative decoupling in production.[27]

In our model, the possibility of decoupling is captured through ϵ_t which measures the ratio between GDP and primary energy use, i.e. the inverse of energy intensity. In order to clarify our assumption, we specify the function $g(\epsilon_t)$ in equation (25).[28] We have

$$\epsilon_{t+1} = \epsilon_t + I_t^{\epsilon} \varsigma(\bar{\epsilon} - \epsilon_t), \tag{27}$$

where the impact of investments (I_t^{ϵ}) on the reduction of energy intensity depends on the difference between the maximum attainable level of energy efficiency $\bar{\epsilon}$ and the actual value of ϵ_t. The closer energy efficiency is to $\bar{\epsilon}$, the lower is the effect on investment. This dynamic aims to take into account two features of decoupling: first, there is a maximum attainable level of dematerialization – energy

[24]Although the Lotka-Volterra model can be exploited to investigate the degree of workers' bargaining power, we believe that this analysis goes beyond the scope of this paper.

[25]For a critical discussion of the issue of decoupling see for instance Antal and van den Bergh (2013) and references therein.

[26]In the more developed economies, energy intensity has decreased three times faster in OECD than in non-OECD countries over the last 25 years Fischer-Kowalski and Swilling (2011)

[27]In Figure 10, the ratio between GDP and energy use – i.e. the inverse of energy intensity, the purple line – and the ratio between GDP and carbon emissions – i.e. the inverse of emission intensity, the green line – increase over time.

[28]Appendix B presents the detailed formulation of this equation used in the simulation, see equations (B.19) and (B.20).

is an essential input of production with bounded substitutability; secondly, an increase in energy efficiency is more likely to occur when efficiency is low. In other words, given a constant level of investment in energy efficiency, the increase in ϵ_t declines over time. Obviously, the higher the value of $\bar{\epsilon}$, the greater is the possibility of decoupling economic growth and energy use. In the baseline scenario, we assume that $\bar{\epsilon} = 18$, which means about three times the average value between 1970-2011 – see the purple path (left scale) in Figure 10.[29]

While this choice does not affect the main results of the model in terms of the amount of investment required to attain a 80% reduction in carbon emissions in 2050 w.r.t. 1990, it becomes crucial when we attempt to evaluate which basket of strategies is more resilient to various sources of uncertainty. We assume two different states of nature that may represent the feasibility of decoupling: a positive one in which decoupling is "easy" – $\bar{\epsilon} = 24$ – and a negative one in which decoupling is "difficult" – $\bar{\epsilon} = 14$. Through different values of ι_ϵ and ι_R, we build two different baskets of investment strategies, the first in which the share of investments in energy efficiency is predominant – called efficiency strategy – and the second in which the main strategy is investments in renewable energy – called renewable strategy. Both the strategies in the positive case are able to meet the target of emissions reduction.

Figure 11 shows the main outcome of this exercise. Economic variables are not significantly affected by changes in $\bar{\epsilon}$ and by the two different strategies, Figure 11a displays this result for the rate of growth. Instead, carbon emissions are very sensitive to this change. Figure 11b shows that the efficiency strategy can induce a faster reduction in carbon emissions if decoupling is "easy" while if decoupling is "difficult", the system ends up very far from the emissions target. On the other hand, the renewable strategy proves more resilient with respect to changes in the feasibility of decoupling although in the positive case the reduction in carbon emissions is slower than that achieved through the implementation of the efficiency strategy. More interestingly, if we consider other sources of uncertainty, for instance an increase in fossil energy price – see Figures 11c and 11d – economic variables considerably depend on the choice of the strategy and on the state of nature on the possibilities of decoupling. Under the negative state of nature, an increase in fossil energy price of 3% per year drastically reduces the rate of growth when the efficiency strategy is chosen, since the economy is unable to reduce its dependence on fossil energy sources. On the other hand, a renewable strategy is more resilient to changes of the state of nature.

In conclusion, although a mix of renewable and efficiency strategies is more

[29] Our initial value of energy efficiency $\epsilon_0 = 9.3$ is higher than that reported in Figure 10. The difference is only due to the fact that GDP in the Figure is at its real value with the reference year 2005, while our reference year is 2010.

efficient from an economic point of view, the development of a renewable energy sector proves more adaptive than a strategy which mainly promotes energy efficiency. First, the development of renewable energy is less affected by uncertainty with respect to the feasibility of decoupling, required to obtain significant results through efficiency improvements. Secondly, a safe domestic energy source allows the system to be less affected by the volatility of the price of fossil fuels and more generally by their availability. This example sheds light on the applicability of the precautionary principle to policy decision making. Irreversibility in the investment decision for carbon emissions abatement calls for careful analysis of the consequences of negative circumstances.

5 Concluding Remarks

Integrated assessment models may help understand the interactions between the socio-economic system and the environment. This paper contributed to this extensive literature by developing an essential macroeconomic model that allows the investigation of the dynamics generated by the implementation of strategies for the transition to a low-carbon economy. The main result is the emergence of a number of tradeoffs between social, economic and environmental indicators which undermine an objective definition of sustainability.

A peculiar feature of the model is the identification of three interacting subsystems, producing extensive feedback and indirect effects. The first is a modified Lotka-Volterra model to determine wages and employment. The second is the traditional growth model that links production to investment, and investment to the accumulation of physical capital. This process endogenously determines labour productivity and hence contributes to establish the level of employment. The third subsystem considers energy an essential input, as well as the economic and environmental consequences of its employment. Investments can be diverted from capital accumulation to three different strategies for emissions abatement, namely improvement in energy efficiency, development of a renewable energy sector, and progress in carbon capture and storage technology.

We compared these strategies by investigating the dynamics generated by the three scenarios: the "reference scenario" which describes the evolution of the system in the absence of green policy; the "current scenario" which represents the implementation of existing energy and mitigation policies; and the "roadmap scenario" that shows the additional investment required to achieve an 80% reduction in carbon emissions in 2050 w.r.t. 1990. In socio-economic terms the results are puzzling, since such a reduction in carbon emissions brings about a slowdown in the growth rate, a decline in the unemployment rate, an increase in the labour share and a reduction in wages. While these effects should tend to reduce inequality, the desirability of such outcomes is a matter for debate.

Finally, we analysed how the model reacts to changes in the values of a few major parameters, namely the price of fossil energy, the number of "green" jobs, and the feasibility of decoupling. In particular, the high degree of uncertainty on decoupling possibilities and on the future trends of fossil energy prices supports the development of a renewable energy sector as the most adaptive strategy which best fits the precautionary principle.

Several important elements in our research remain unexplored. However, thanks to the flexibility of the methodology adopted, we leave two interesting extensions for future research. First, the role of government can be formalised in greater detail. For instance, in order to make the returns in the "green economy" competitive and to obtain the desired amount of "green investment", public incentives may be necessary. Thus, the national fiscal position and budget limitations can be detrimental for achieving emissions targets.

A second extension of the model may explore the dynamics of credit creation and the interactions of the banking sector with the rest of the economic system.[30] These two extensions may help shed light on how the socio-economic system could finance the transition to a low-carbon society.

References

Antal, M. and J. C. van den Bergh (2013). Macroeconomics, financial crisis and the environment: Strategies for a sustainability transition. *Environmental Innovation and Societal Transitions 6*(0), 47 – 66.

ASPO (2008). ASPO newsletter no 95. Technical report, www.aspo-ireland.org.

Bardi, U. (2011). *The Limitis to Growth Revised.* Springer.

Barker, T., A. Anger, A. Chewpreecha, and H. Pollitt (2012). A new economics approach to modelling policies to achieve global 2020 targets for climate stabilisation. *International Review of Applied Economics (Special issue: Economic Policies of the New Thinking in Economics)*, 205–211.

Bassi, A. (2008). *Modeling US energy policy with Threshold 21.* VDM: Saarbrücken, Germany.

Bassi, A., R. Powers, and W. Schoenberg (2010). An integrated approach to energy prospects for north america and the rest of the world. *Energy Economics 32*, 30–42.

Bernardo, G. and E. Campiglio (2013). A simple model of income, aggregate demand and the process of credit creation by private banks. *Empirica*, available online since December 2013.

Bernardo, G. and S. D'Alessandro (2014). Transition to sustainability: Italian scenarios toward a low-carbon economy. *Lecture Notes in Computer Science 7991*, forthcoming.

[30] See for instance Ryan-Collins et al. (2012); Bernardo and Campiglio (2013).

Bilancini, E. and S. D'Alessandro (2012). Long-run welfare under externalities in consumption, leisure, and production: A case for happy degrowth vs. unhappy growth. *Ecological Economics 84*(0), 194 – 205.

Boulding, K., H. Daly, and N. Georgescu-Roegen (1974). Toward a human economics. *American Economic Review 64*(2), 449–450.

Capros, P., T. Georgakopoulos, D. van Regemorter, S. Proost, T. Schmidt, and K. Conrad (1997). European union: the gem-e3 general equilibrium model. *Economic and Financial Modelling*, 51–161.

Costanza, R., I. Kubiszewski, E. Giovannini, H. Lovins, J. McGlade, K. Pickett, K. Ragnarsdottir, D. Roberts, R. D. Vogli, and R. Wilkinson (2014). Time to leave gdp behind. *Nature 505*, 283–285.

Costanza, R. and M. Ruth (1998). Using dynamic model to scope environmental problems and build consensus. *Environmental Management 22*, 183–195.

Costanza, R., L. Wainger, C. Folke, and K.-G. Maler (1993). Modeling complex ecological economic systems: toward an evolutionary, dynamic understanding of people and nature. *BioScience 43*, 545–555.

D'Alessandro, S., T. Luzzati, and M. Morroni (2010). Energy transition towards economic and environmental sustainability: feasible paths and policy implications. *Journal of Cleaner Production 18*, 291–298.

Daly, E. H. (1996). *Beyond Growth: The Economics of Sustainable Development*. Boston: Beacon Press.

EIA (2007). International energy outlook 2007, energy information administration. Technical report, US department of energy.

ENEA (2012). Rapporto energia ambiente. Technical report, National agency for new technologies, Energy and sustainable economic development.

European Commission (2011). A roadmap for moving to a competitive low carbon economy in 2050. Technical report, SEC 288.

Fischer-Kowalski, M. and M. Swilling (2011). Decoupling natural resource use and environmental impacts from economic growth. Technical report, United Nations Environment Programme.

Flaschel, P. (2010). *The Macrodynamics of Capitalism - Elements for a Synthesis of Marx, Keynes and Schumpeter*. Berlin: Springer Verlag Berlin.

Foley, D., L. Taylor, and A. Rezai (2013). The social cost of carbon emissions. *INET Research Notes 28 - Institute for New Economic Thinking (INET)*.

Funtowicz, S. and J. Ravetz (1990). *Uncertainty and Quality in Science for Policy*. the Netherlands: Kluwer Academic Publishers.

Funtowicz, S. and J. Ravetz (1991). A new scientific methodology for global environmental issues. In R. Costanza (Ed.), *Ecological Economics: The Science and Management of Sustainability.* New York: Columbia University Press.

Georgescu-Roegen, N. (1971). *The entropy law and the economic process.* Cambridge: Harvard University Press.

Goodwin, R. M. (1967). "a growth cycle". In C. Feinstein (Ed.), *Socialism, Capitalism and Economic Growth.* Cambridge: Cambridge University Press.

Harris, J. (2009). Ecological macroeconomics: consumption, investment, and climate change. *Real-World Economics Review 50*, 34–48.

Jackson, T. (2009). *Prosperity without Growth. Economics for a Finite Planet.* Earthscan.

Jackson, T. and P. Victor (2011). Productivity and work in the new economy – some theoretical reflections and empirical tests. *Environmental Innovation and Societal Transitions 1*, 101–108.

Liebard, A. (2012). The state of renewable energies in europe. Technical report, Observ'ER.

Lotka, A. J. (1932). The growth of mixed populations: two species competing for a common food supply. *Journal of the Washington Academy of Sciences 22*, 461–469.

Loulou, R. and M. Labriet (2008). Etsap-tiam: the times integrated assessment model part i: Model structure. *Computational Management Science 5*, 7.

Meadows, D., D. Meadows, and J. Randers (1972). *The Limits to Growth.* New York: Universe Books.

Meadows, D., D. Meadows, and J. Randers (1991). *Beyond the limits : global collapse or a sustainable future.* Earthscan.

Nail, R. and P. Budzik (1976). Fossil1: A policy analysis model of the u.s. energy transition. *WSC '76 Proceedings of the 76 Bicentennial conference on Winter simulation*, 145–152.

Nordhaus, W. (2008). A question of balance. weighing the options on global warming policies. *New Haven, Yale University Press*.

Nordhaus, W. (March 1993). Rolling the 'dice': an optimal transition path for controlling greenhouse gases. *Resource and Energy Economics-Elsevier 15*, 27–50.

Rezai, A., D. Foley, and L. Taylor (2012). Global warming and economic externalities. *Economic Theory 49*, 329–351.

Ryan-Collins, J., T. Greenham, R. Werner, and A. Jackson (2012). *Where does money come from?* New Economics Foundation.

Sararzynska, K. and J. van den Bergh (2013). An evolutionary model of energy transitions with interactive innovation-selection dynamics. *Journal of Evolutionary Economics 23*, 271–293.

Scrieciu, S., A. Rezai, and A. Mechler (2013). On the economic foundations of green growth discourses: the case of climate change mitigation and macroeconomic dynamics in economic modeling. *WIREs - Energy Environment 2*, 251–268.

Sterman, J. (1982). A dynamic, disequilibrium model of energy-economy interactions. *International Journal of Energy Systems 2*, 159–163.

Stern, N. (2007). *The Economics of Climate Change: The Stern Review.* Cambridge University Press.

UNEP (2011). Towards a green economy: Pathways to sustainable development and poverty eradication. *www.unep.org/greeneconomy*.

Victor, P. A. (2008). *Managing without growth:slower by design, not disaster.* Cheltenham: Edward Elgar.

Victor, P. A. (2012). Growth, degrowth and climate change: A scenario analysis. *Ecological Economics 84*(0), 206 – 212.

Victor, P. A. and G. Rosenbluth (2007). Managing without growth. *Ecological Economics 61*, 492–504.

Volterra, V. (1926). "variations and fluctuations of the number of individuals in an animal species living together". In R. N. Chapman (Ed.), *In Animal Ecology.* (Reprinted in 1931. McGraw Hill, New York).

Wei, M., S. Patadia, and D. M. Kammena (2010). Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the us? *Energy Policy 38*, 919–931.

Wheat, D. (2003). Macrolab model-facilitated learning of essential macroeconomics. *http://www.systemdynamics.org/conferences/2003/proceed/PAPERS/337.pdf*.

Yamaguchi, K. (2011). Macroeconomic dynamics - accounting system dynamics approach. *3rd Draft*.

Appendices

A Variables and parameters

List of variables

E	Total energy use
Q	Fossil energy use
H	Renewable energy use
R	Renewable energy capacity
CO_2	carbon emission
Y	Production
GDP	Gross domestic product
λ	Labour productivity
K	Capital stock
LF	Labour force
p	Price of fossil energy
ϵ	Energy intensity
V^I	Employment rate in the final sector
κ	Capital productivity
w	Real wage
ϕ	Carbon emission intensity per units of fossil energy
L^I	Workers in the final sector
L^E	Workers in the energy sector
L^H	Direct workers in the renewable energy sector
L^R	Indirect workers in renewable energy sector
L^ϵ	Workers in energy efficiency sector
L^M	Workers in mitigation sector
L^Q	Workers in non renewable energy sector
L	Total workers
u	Unemployment rate
W	Gross Total wage
Π	Gross Total profits
ν_w	Labour share
ν_k	Profits share
T	Total tax
TR	Unemployment benefits
G	Governament expenditure
S	Saving
I	Investment
I^ϵ	Investment in energy efficiency
I^R	Investment in renewable energy
I^M	Investment in carbon capture and storage
I^K	Investment in productive capital

List of parameters

$$h = 1$$
$$\bar{u} = 0.08$$
$$\alpha = 0.7$$
$$\beta_1 = 0.05$$
$$\beta_2 = 3000$$
$$\gamma_1 = 0.4$$
$$\gamma_2 = 0.9$$
$$\delta_k = 0.027$$
$$\delta_r = 0.01$$
$$\bar{\epsilon} = 18$$
$$\eta = 0.35$$
$$\theta = 0.9$$
$$\Lambda = 72.9$$
$$\mu = 0.6$$
$$o = 10000$$
$$\rho = 0.01$$
$$\rho_0 = 1$$
$$\rho_1 = 2$$
$$\rho_2 = 6$$
$$\rho_3 = 0.000099$$
$$\sigma_1 = 1.2$$
$$\sigma_2 = 1.875$$
$$\sigma_3 = 2$$
$$\sigma_4 = 1.82$$
$$\sigma_5 = \frac{2}{3}$$
$$\tau_1 = 0.3$$
$$\tau_2 = 0.24$$
$$\psi = 0.2$$
$$g_{\varrho^\epsilon} = 0$$
$$g_{\varrho^H} = 0$$
$$g_{\varrho^R} = 0$$
$$g_p = 0$$
$$g_n = 0.02$$
$$g_\kappa = 0.01$$

Stocks: initial values

$$K_0 = 9696810$$
$$\epsilon_0 = 9.3$$
$$LF_0 = 24900$$
$$V_0^I = 0.907$$
$$w_0 = 46$$
$$\kappa_0 = 0.002328$$
$$p_0 = 0.6$$
$$\phi_0 = 1.28$$
$$\varrho_0^H = 0.0017$$
$$\varrho_0^R = 0.12$$
$$\varrho_0^\epsilon = 0.022$$
$$\varrho_0^\phi = 0.022$$
$$\varrho_0^Q = 0.0001$$

Policy parameters

	Reference	Current	Roadmap
ι_ϵ	0.01	0.01+ RAMP(0.005 , 4 , 7)	0.001 +RAMP(0.005 , 4, 18)
$\iota_{\mathbf{R}}$	0.01	0.01 + RAMP(0.01 , 4 , 9)	0.01 + RAMP(0.02 , 4 , 13)
$\iota_{\mathbf{M}}$	0.001	0.01	0.001 + RAMP(0.005 , 4 , 6)

Table 2: Green Investment Strategy

Figure 12 shows the resulting value of $\iota_K = 1 - \iota_\epsilon - \iota_R - \iota_M$ in the three scenarios.

B List of Equations

Energy sector

$$E_t = Q_t + H_t \tag{B.1}$$

$$H_t = hR_t \tag{B.2}$$

$$R_{t+1} = R_t + I_t^R\ f(R_t) - \delta^R(R_t - \bar{R}), \tag{B.3}$$

$$f(R_t) = \rho_0 + (\rho_1/(1 + EXP(\rho_2 - \rho_3 R_t))) \tag{B.4}$$

$$Q_t = \frac{f\left(L^F, K, \lambda, t\right)}{\epsilon_t} - H_t. \tag{B.5}$$

$$CO_2 = \frac{\phi_t Q}{o} \tag{B.6}$$

GDP

$$Y_t = \min\left\{f\left(L^F, K, \lambda, t\right), \epsilon_t E_t\right\}, \tag{B.7}$$

$$f(L^F, K, \lambda, t) = \Lambda\left[\alpha\left(\lambda_t L_t^F\right)^{\frac{\theta-1}{\theta}} + (1-\alpha)\left(\kappa_t K_t\right)^{\frac{\theta-1}{\theta}}\right]^{\frac{\theta}{\theta-1}}, \tag{B.8}$$

$$GDP_t = Y_t - p_t Q_t. \tag{B.9}$$

Labour productivity

$$\zeta = \left(\frac{1}{K_0}\right)^\mu \tag{B.10}$$

$$\lambda_t = \zeta K_t^\mu \tag{B.11}$$

Stock variables

$$K_{t+1} = (1-\delta^k)K_t + I_t^k \tag{B.12}$$

$$LF_{t+1} = (1+g_n)LF_t \tag{B.13}$$

$$p_{t+1} = p_t + g_p \tag{B.14}$$

$$\epsilon_{t+1} = \epsilon_t + I_t^{\epsilon} * g(\epsilon_t) \tag{B.15}$$

$$v_{t+1}^I = v_t^I(1+g_{v^I}) \tag{B.16}$$

$$\kappa_{t+1} = \kappa_t + g_{\kappa} \tag{B.17}$$

$$w_{t+1} = w_t(1+g_w) \tag{B.18}$$

$$\epsilon_{t+1} = \epsilon_t + I_t^{\epsilon} g_{\epsilon_t} \tag{B.19}$$

$$g_{\epsilon_t} = MAX(\varsigma(\bar{\epsilon} - \epsilon_t), 0) \tag{B.20}$$

$$\phi_{t+1} = \phi_t + \zeta_t^m \tag{B.21}$$

$$\zeta_t^m = \phi_t I^{M\eta} \tag{B.22}$$

Lotka-Volterra

$$\begin{cases} g_{v^I} = (A_t - B_t w_t) & \text{(B.23)} \\ g_w = (C_t v_t^I - D_t). & \text{(B.24)} \end{cases}$$

$$\begin{aligned} A_t &= \sigma_1 \frac{GDP_t}{K_t} - n - \lambda_t, & \text{(B.25)} \\ B_t &= \sigma_2 \frac{L_t^I}{K_t}, & \text{(B.26)} \\ C_t &= \sigma_3 \lambda_t^{\psi}, & \text{(B.27)} \\ D_t &= \sigma_4 - \sigma_5 v_t^E. & \text{(B.28)} \end{aligned}$$

Employment

$$L_t^I = v_t^I LF_t \tag{B.29}$$

$$L_t^E = L_t^H + L_t^R + L_t^\epsilon + L_t^M + L_t^Q. \tag{B.30}$$

$$L_t^H = H_t \varrho_t^H \tag{B.31}$$

$$L_t^R = (R_t - R_{t-1})\varrho_t^R \tag{B.32}$$

$$L_t^\epsilon = (\epsilon_t - \epsilon_{t-1})\varrho_t^\epsilon \tag{B.33}$$

$$L_t^\phi = (\phi_t - \phi_{t-1})\varrho_0^\phi \tag{B.34}$$

$$L_t^Q = Q_t \varrho_0^Q \tag{B.35}$$

$$\varrho_{t+1}^H = \varrho_t^H + g_{\varrho^H} \tag{B.36}$$

$$\varrho_{t+1}^R = \varrho_t^R + g_{\varrho^R} \tag{B.37}$$

$$\varrho_{t+1}^\epsilon = \varrho_t^\epsilon + g_{\varrho_\epsilon} \tag{B.38}$$

$$L_t = L_t^E + L_t^I \tag{B.39}$$

$$u_t = \frac{LF_t - L_t}{L_t} \tag{B.40}$$

Labour and profit share

$$W_t = w_t L_t^I + w_t L_t^E \tag{B.41}$$

$$\Pi_t = GDP_t - W_t \tag{B.42}$$

$$\begin{cases} \nu_k = \dfrac{\Pi_t}{GDP_t} & \text{(B.43)} \\ \nu_w = \dfrac{W_t}{GDP_t}. & \text{(B.44)} \end{cases}$$

Aggregate demand

$$T_t = \tau_1 \Pi_t + \tau_2 W_t \tag{B.45}$$

$$TR_t = \beta_1 GDP_t + \beta_2 (u_t - \bar{u}) \tag{B.46}$$

$$G_t = T_t - TR_t \tag{B.47}$$

$$C_t = (1-\tau_1)\gamma_1 \Pi_t + (1-\tau_2)\gamma_2 W_t \tag{B.48}$$

$$S_t = I_t = (1-\tau_1)(1-\gamma_1)\Pi_t + (1-\tau_2)(1-\gamma_2) W_t \tag{B.49}$$

$$AD_t = C_t + G_t + I_t \tag{B.50}$$

Investment strategy

$$I_t^{\epsilon} = I_t \iota_{\epsilon} \tag{B.51}$$

$$I_t^{R} = I_t \iota_{R} \tag{B.52}$$

$$I_t^{M} = I_t \iota_{M} \tag{B.53}$$

$$I_t^{K} = I_t \iota_{K}. \tag{B.54}$$

6 List of Figures

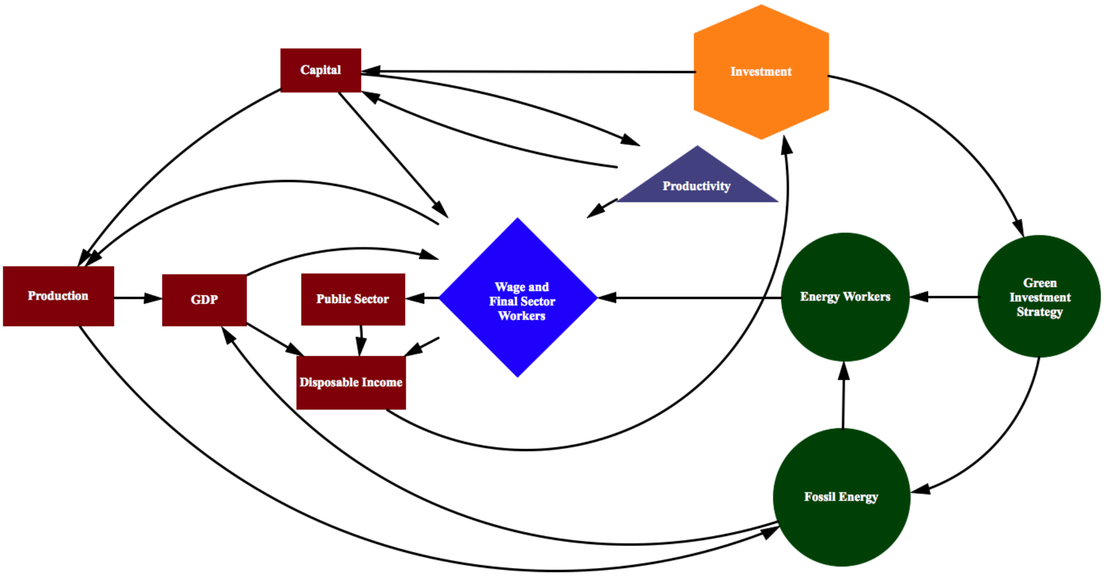
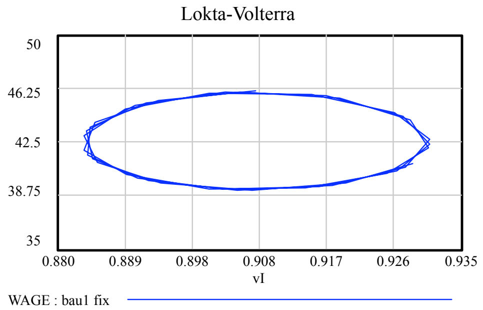
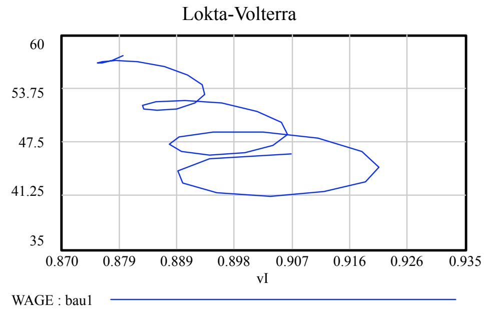


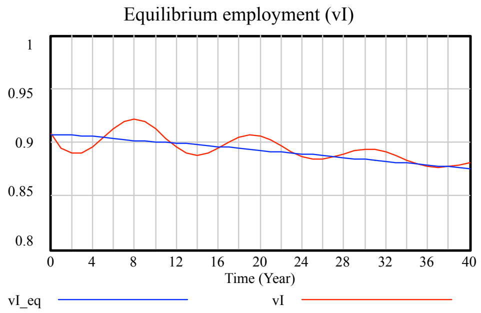
Figure 1: The causal structure of the model: an aggregate view.



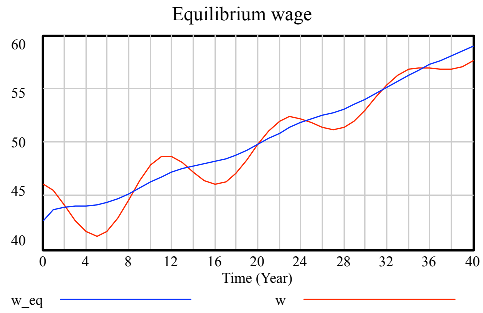
(a) Standard predator-prey model



(b) Modified predator-prey model



(c) The trajectory of the employment rate (red) around the fixed point (blue)



(d) The trajectory of the wage (red) around the fixed point (blue)

Figure 2: Predator-prey dynamics for the determination of wage and employment.

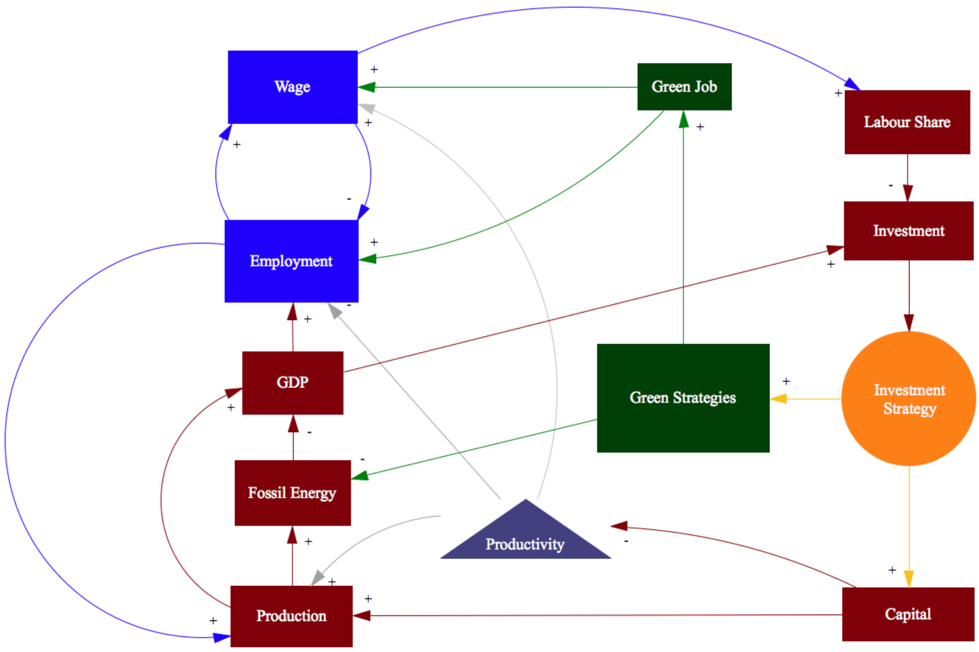
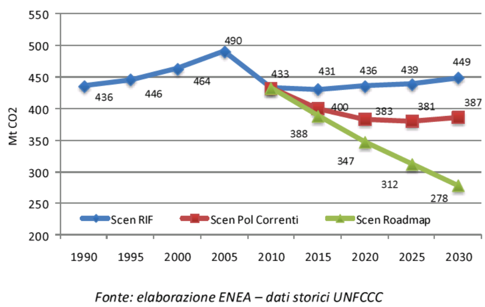
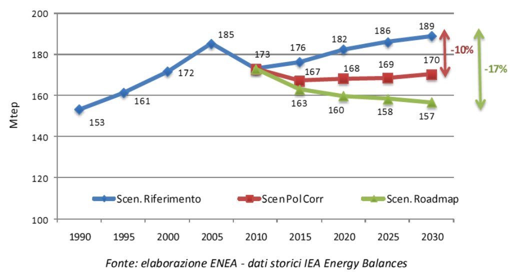


Figure 3: Causal mapping and feedbacks interactions.



(a) Primary Energy Consumption



(b) CO2 Emissions

Figure 4: ENEA (2012) scenarios for Italy. Reference Scenario (blue); Current Policies Scenario (red); Roadmap Scenario (green).

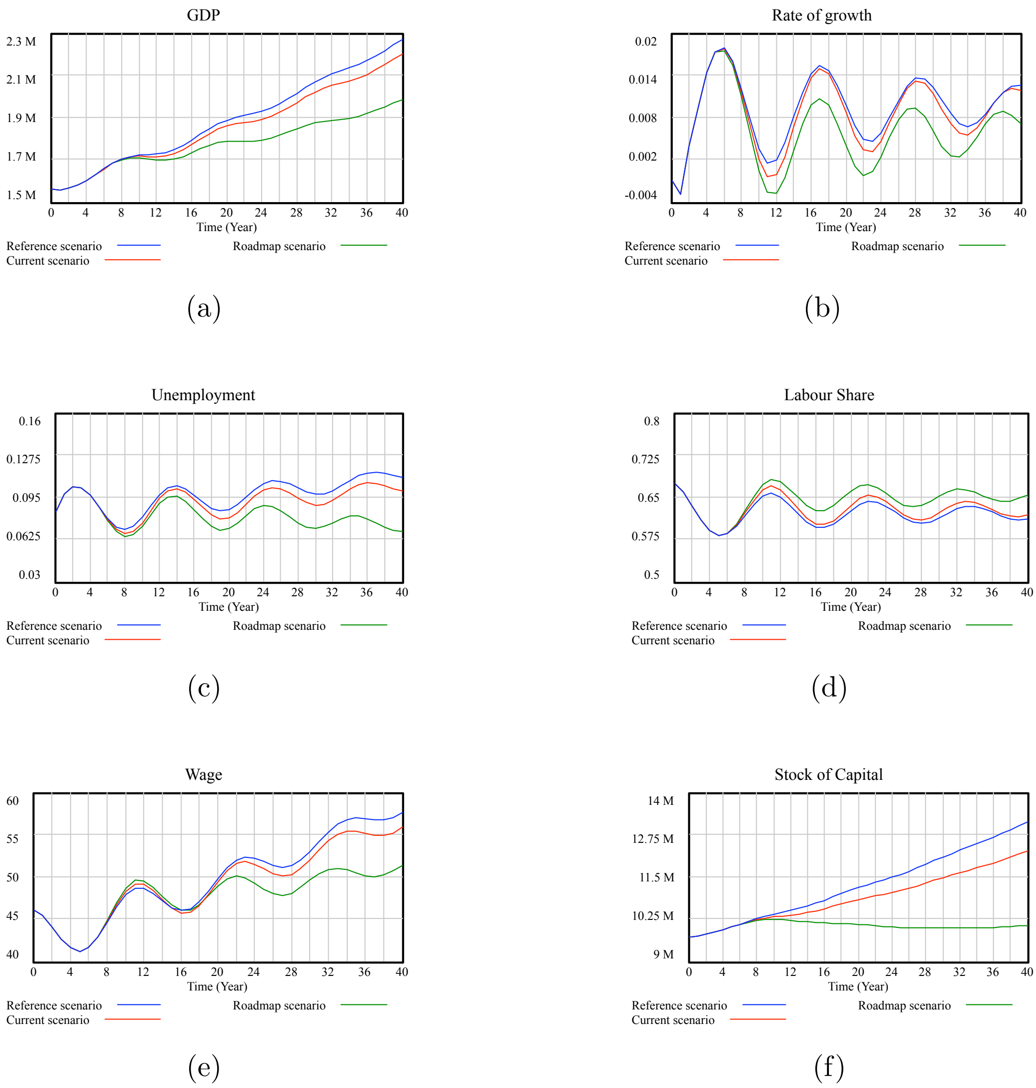


Figure 5: Scenario analysis: socio-economic indicators.

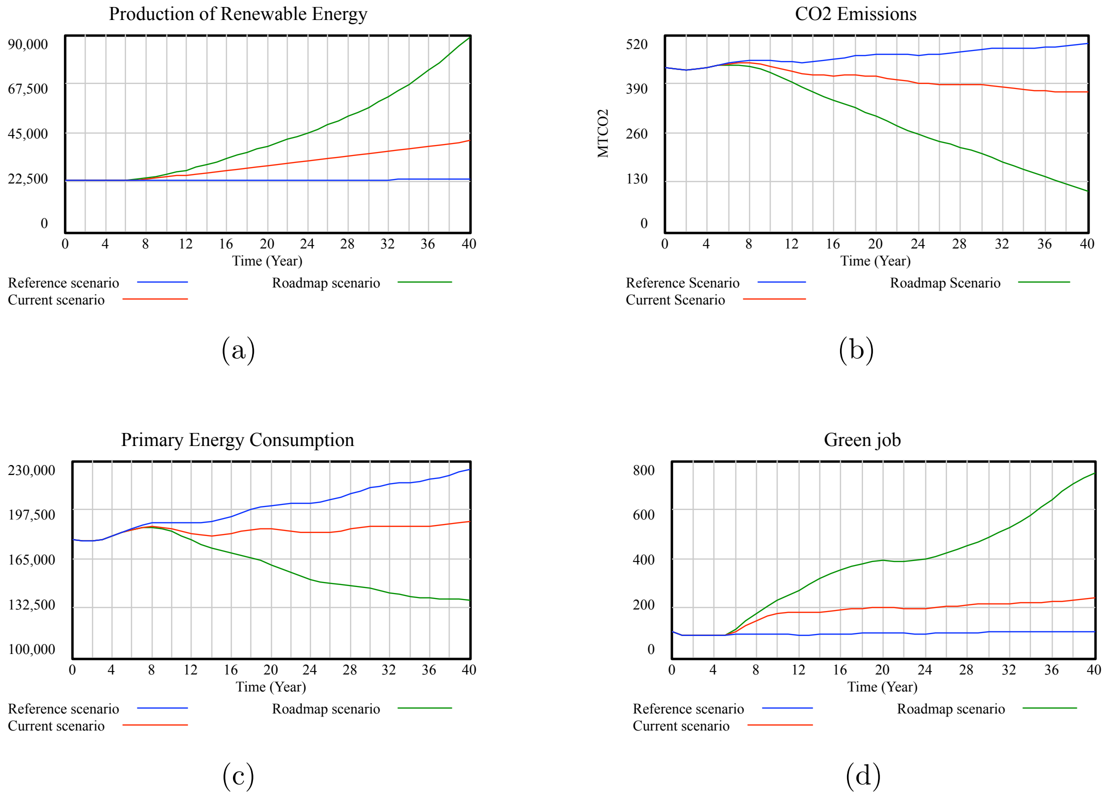
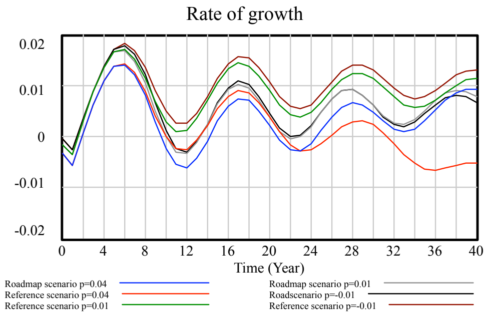
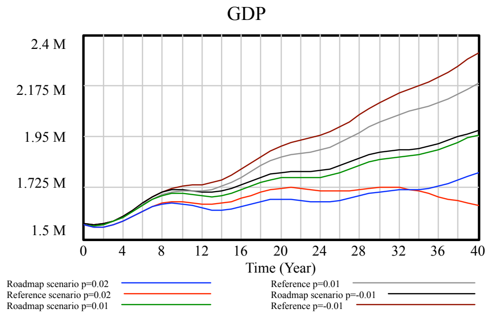


Figure 6: Scenario analysis: energy sector and carbon emissions.



(a)



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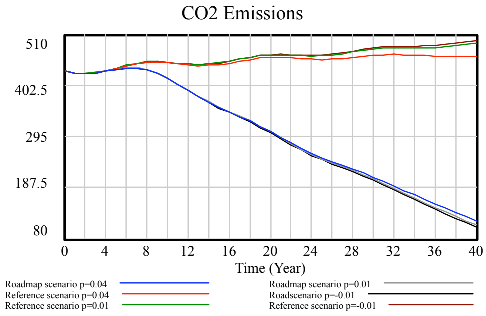

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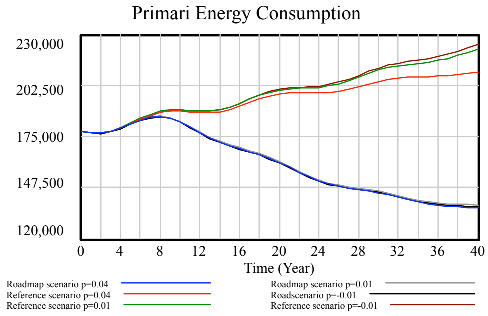
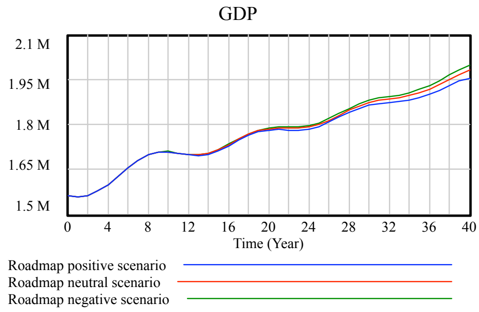
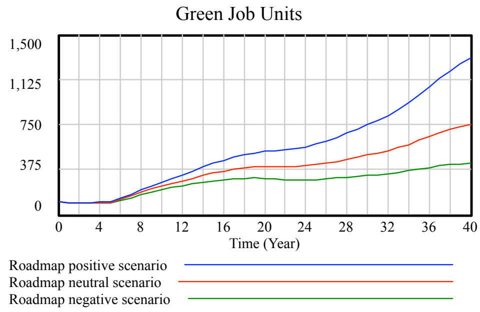


(d)

Figure 7: Sensitivity analysis: price of fossil energy sources.



(a)



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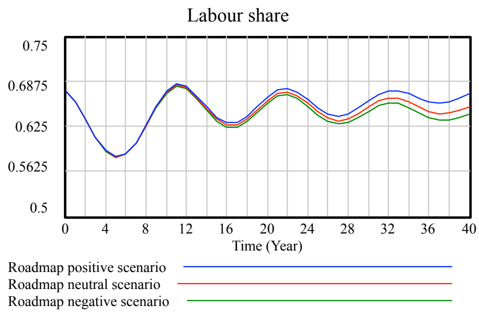
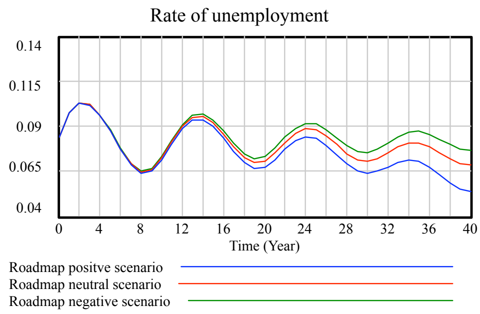
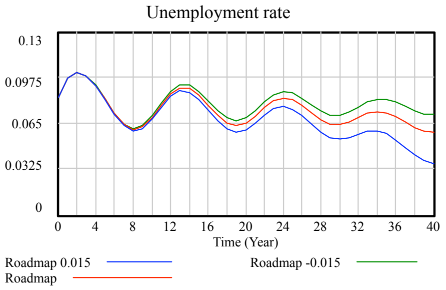


(c)

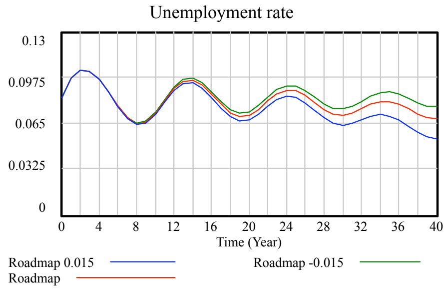


(d)

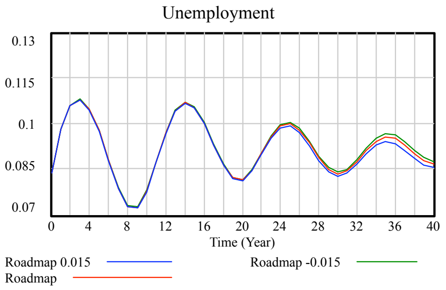
Figure 8: Sensitivity analysis: units of green workers



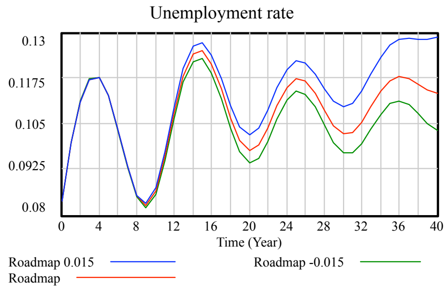
(a) $\sigma_5 = 0$



(b) $\sigma_5 = \frac{2}{3}$



(c) $\sigma_5 = 2$



(d) $\sigma_5 = 4$

Figure 9: Sensitivity analysis: the elasticity of wage w.r.t. the rate of employment in the energy sector

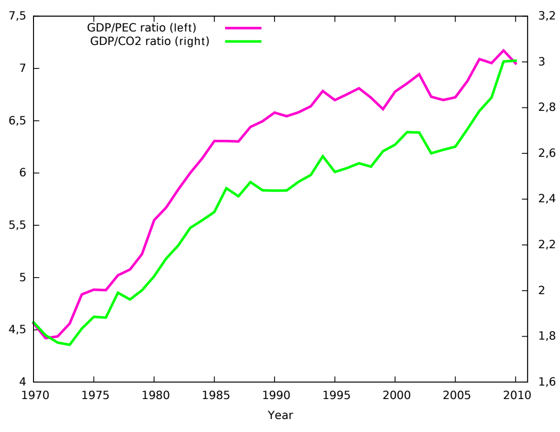


Figure 10: Relation between real GDP, CO_2 emissions and primary energy consumption. Sources: ISTAT - chain linked reference year 2005, The World Bank and BP Statistical Review of World Energy, June 2013

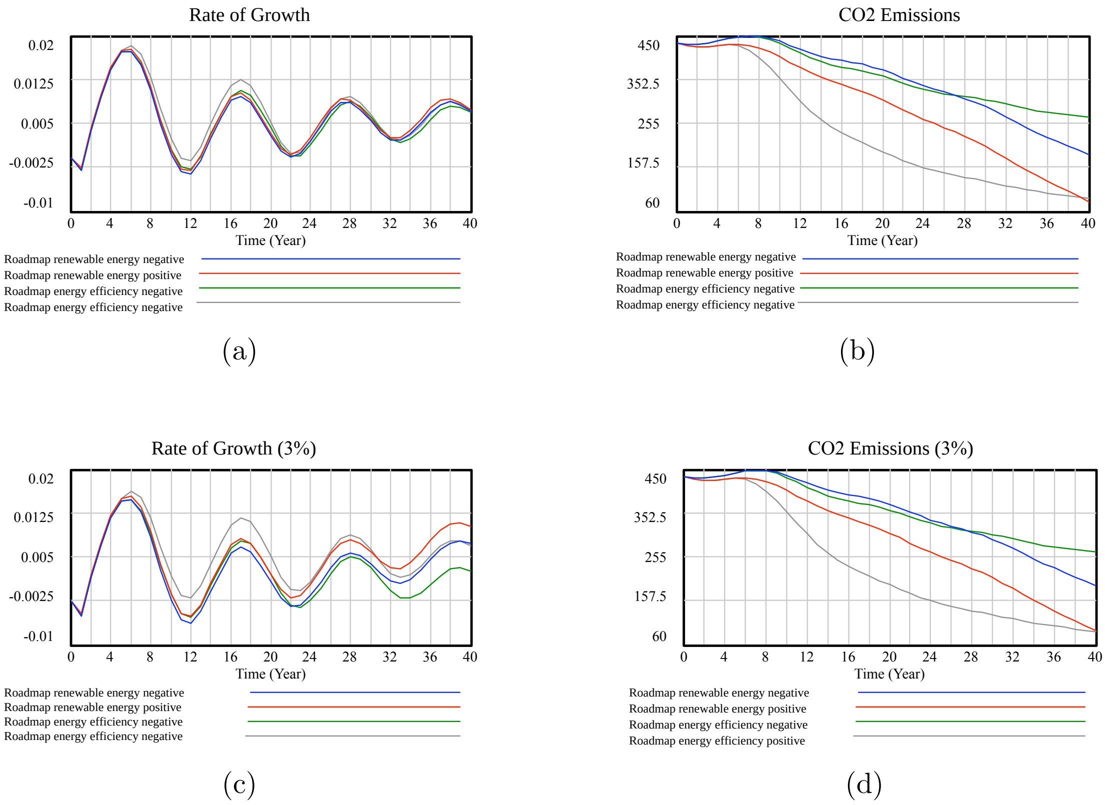


Figure 11: Sensitivity analysis: decoupling and fossil energy dependence.

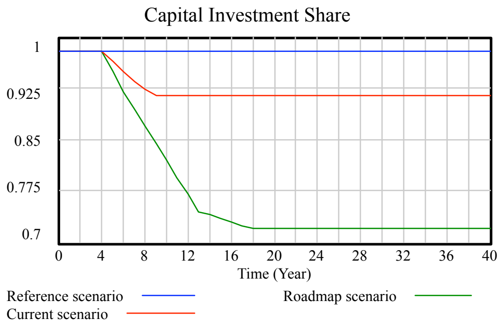


Figure 12: Capital investment share